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AST Combustion Workshop: Diagnostics Working Group Report

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ABSTRACT

A workshop was convened under NASA's Advanced Subsonics Technologies (AST) Program. Many of the principal combustion diagnosticians from industry, academia, and government laboratories were assembled in the Diagnostics/Testing Subsection of this workshop to discuss the requirements and obstacles to the successful implementation of advanced diagnostic techniques to the test environment of the proposed AST combustor. The participants, who represented the major relevant areas of advanced diagnostic methods currently applied to combustion and related fields, first established the anticipated AST combustor flowfield conditions. Critical flow parameters were then examined and prioritized as to their importance to combustor/fuel injector design and manufacture, environmental concerns, and computational interests. Diagnostic techniques were then evaluated in terms of current status, merits and obstacles for each flow parameter. All evaluations are presented in tabular form and recommendations are made on the best-suited diagnostic method to implement for each flow parameter in order of applicability and intrinsic value.

BACKGROUND

The Advanced Subsonics workshop was called to assemble researchers in the United States aerospace community for the purpose of evaluating the requirements and obstacles to the establishment and successful implementation of a U.S. Advanced Subsonics Technologies Program (AST). The general workshop was subdivided into five working groups: CFD, Diagnostics and Testing, Chemistry and Soot, Fuel Injection, and Combustor Liners and Cooling. Each subgroup was to discuss and evaluate their working topic guided by three

objectives: 1) Determine the technology that needs to be applied or developed; 2) Identify roadblocks and obstacles to implementing this technology; and, 3) Ascertain methods for overcoming these obstacles.

The Diagnostic/Testing subsection brought together many of the principal combustion diagnosticians from industry, academia, and government laboratories to discuss the requirements for successful implementation of advanced diagnostic techniques to the test environment of the proposed AST combustor. The participants represented the major relevant areas of advanced diagnostic methods currently applied to combustion and related fields. The following text and tables summarize the general consensus of the Diagnostics/Testing subsection's findings and recommendations.

DISCUSSION

The three objectives to guide the discussion section were modified to read: 1) Determine what measurements are necessary; 2) Determine what diagnostic method to apply to each parameter determined in (1) above; and, 3) Determine what, if any, are the obstacles to obtaining the desired measurements and what can be accomplished to overcome or circumvent these obstacles. A general overview of the advanced subsonic combustor rig (ASCR) was given to aid the process of determining which measurement to make, and hence, which corresponding diagnostic technique to apply. The anticipated design for an optically accessible ASCR, capable of withstanding pressures of 60 atm and temperatures of 3200°F was obtained after consulting with NASA Lewis Design Engineering.

A configuration providing 4 circumferentially located, fused silica windows, spaced 90° apart, and approximately 0.75″- 1.25″ in diameter, was deemed feasible. The windows would be positioned approximately 4.0″ downstream from the present fuel injector location. Additional window positions would be possible at other axial locations as determined by a specific diagnostic technique. The design would permit the utilization of most applicable non-intrusive optical diagnostic methods. Additionally, it was noted that to provide the best opportunity for securing data in this test regime, the windows should be positioned at the fuel-injector exit plane. The attendees were advised that modifications to extend the fuel injectors to the leading edge of the windows were being considered. The consensus of those in attendance was that the window design and placement as described would be adequate, but cautioned that smaller windows would seriously limit the application of many optical methods.

The initial concern for the Diagnostics subsection was to ascertain which measurements were mandated to satisfy requirements established by engine manufacturers, CFD code validation, fuel-injector design, and environmental concerns. Having established and subsequently prioritized these parameters, the discussion focused on the determination of which diagnostic methods should be applied to each parameter. It was determined that conceivably only six measurement categories would be required to provide feedback on the technical issues mandated by the various AST concerns. Those regimes were prioritized as follows: 1) NO; 2) Temperature; 3) Flow Field Imaging, subdivided into a) reacting flows, and b) non-reacting flows; 4) Sprays; 5) Soot; and 6) Velocity.

Each measurement category was examined individually by the working group, and diagnostic methods for each were considered. Potential diagnostic methods were examined and analyzed for their applicability, accuracy, sensitivity, simplicity, reliability and other merits, and limitations. Those methods determined to be plausible candidates for any of the six categories were then listed in approximate order of their perceived weighted benefits. Relevant ancillary information was also tabulated with each technique.

The participants agreed that direct measurement of NO or NO_X would be crucial to the AST program, much as it is to the High Speed Research (HSR) program, owing to its contribution to surface-level smog and its deleterious effect on stratospheric ozone. Thus this parameter was discussed first and with particular thoroughness. The best suited diagnostic methods for detection of NO generated in the ASCR, estimated in the 5-500 ppm range, are listed in Table I.

Table I

Summary of Methods (NO)

Method	Status	Merits	Obstacles
PLIF (UV)	-done to 45 atm	-relatively simple -two-D information -semi quantitative	-influence of soot, PAH -influence of O_2 fluorescence
LIF (UV)	-done to 45 atm	- ± 10% accuracy	-influence of O_2 fluorescence -single point measurement
Line-of-Sight Absorption (LOSA)	-done in IR/UV -line-of-sight	-simple -fast -potential high accuracy	-IR limited to extracted gas sample -UV limited to exit plane
Sample Extraction	-established	-simple -coupled with LOSA to improve speed -potential high accuracy	-flow perturbing -sample line chemistry -test time

Both LIF and PLIF for measuring NO have been intensively investigated. However, in this country, these studies have been limited in pressure to 10 - 15 atm, corresponding to the conditions of interest to HSR. It is therefore regarded as critical that preparative diagnostic studies be performed at pressure to at least 60 atm to investigate issues that may be problematic to PLIF and LIF at the pressure and temperature regimes of the ASCR. These issues include optical interference from complex fuel chemistries, quenching contributions, and rotational-energy transfer (RET). It should be noted that the physics underlying PLIF and LIF is the same, but PLIF is somewhat more problematic because of limitations and filter/detector options. PLIF, however, is advantageous owing to its ability to provide information on instantaneous spatial distributions.

The diagnostic techniques outlined above for NO, and additional techniques, such as linear Raman, which has met with recent success at AST pressures in European laboratories, can also be applied to other molecular ($OH^{\cdot}$, O_2, SO_2, CH, etc...) and atomic species ($O^{\cdot}$, $H^{\cdot}$, etc...). These supplementary, affiliated combustion species should be investigated for other AST related diagnostic applications in addition to CFD or analytical issues. As noted in

Table I, LIF and PLIF work has already been initiated at pressures approaching that expected for the AST program, but this body of work has been instituted in Germany and Japan. We believe this confirms the working group's recommendation of these techniques as the most appropriate for monitoring the extreme high-pressure combustion environments in the AST program.

Following NO, temperature was regarded as the next most critical parameter to be measured. Table II presents those diagnostic methods that the working group believed to be most capable of measuring temperature in the ASCR environment.

Table II

Summary of Methods (Temperature)

Method	Status	Merits	Obstacles
CARS	-relatively mature -single "point" -used to 50 atm	- ± 3% (t average) -used to 50 atm	-gradients -complex scheme -point measurement
RAMAN	-relatively mature -point or line measurement	-simultaneous measurement of multiple species	-soot incandescence -point measurement
Laser-Induced Fluorescence (LIF)	-relatively mature -used to 5 atm	-multiple species ($OH^{\cdot}$, NO, O_2, atoms)	-pressure effects -soot effects
Planar Laser-Induced Fluorescence (PLIF)	-used to 5 atm	-2-d information -multiple species	-pressure effects -soot effects
Line-of-Sight Absorption (LOSA)	-used at 1 atm -line-of-sight	-multiple species (CO, CO_2, H_2O, O_2)	-pressure limited
Line Reversal	-well developed -used at 1 atm	-simple	-line average temp. -pressure effects
Transient or Thermal Gradient Spectroscopy	-unproven	-similar to CARS	-high risk -long development
Rayleigh	-used at 1 atm -point or line measurement	-simple	-point measurement

Non-intrusive diagnostic-based temperature measurements can complement traditional gas-phase temperature sensors, especially since the severe operating environment of the AST combustor pushes the limits of existing uncooled thermocouple development. A detailed knowledge of temperature profiles within the ASCR is a critical requirement for combustor design, liner materials, as well as for environmental issues. However, temperature is also difficult to monitor with high accuracy. The diagnostic methods which have demonstrated a degree of success at AST conditions are primarily point or linear techniques. The planar techniques for measuring temperature have not as yet been attempted at the requisite conditions of the ASCR, but instantaneous planar measurement of temperature would prove especially valuable in ASCR studies. The working group noted the necessity for small-scale laboratory facilities in which to extend planar measurements to AST conditions for the purpose of measuring temperature profiles. These profiles are vitally important to pattern factor derivation, heat release validation and chemical-reaction mechanism and rate determination.

Techniques that would avail themselves to imaging and evaluating reacting flow characteristics were discussed next: summary comments are given in Table III. Most of the diagnostic methods listed have been used with varying degrees of success at pressures approaching those expected in the ASCR.

Table III

Summary of Methods (Flow Field)
Reacting Flow Field Imaging

Method	Status	Merits	Obstacles
PLIF	-done to 50 atm in internal combustion engines (Germany)	-qualitative 2-D -multiple species (OH^-, Unburned Hydrocarbons) -useful for primary and secondary zone -temperature obtainable	-pressure effects -soot interference -Polycyclic aromatic hydrocarbon (PAH) effects
Raman	-line imaging	-simultaneous multiple species (fuel, O_2, H_2O, N_2) -quantitative -temperature obtainable	-emission interferences
CARS	-line imaging -done to 30 atm	-multiple species -quantitative	-gradients -emission interferences
Focused Schlieren	-developed	-mixing zone images -heat release zones -simple -potential 3-D	-non-specific
Tracers	-established (particulates, tagged fuel, gas, etc...)	-useful for screening -simple -two dimensional	-facility concerns

It is expected that imaging data acquired in reacting flows will be of extreme importance to designers and modelers to aid in their understanding of the mixing and post-combustion zones, and also in validating submodels of CFD codes. The working group assigned high priority to the need for collaboration between CFD modelers and diagnosticians in planning work to validate CFD codes. The imaging techniques listed in Table I appear again in Table III. In application to a reacting flow, NO need not necessarily be imaged, and for utilitarian reasons, would not be the species of choice: Rather, a major product, tracer, an intermediate species such as OH^- or CH^-, or unburned hydrocarbons would be better suited. However, quenching as well as other concerns that would affect quantitative PLIF measurements of these species will remain an issue at these conditions and will require evaluation. The potential facility concerns involving tracers include possible line clogging, undesired chemical interactions, environmental safety, and seed-introduction method. Any problem associated with these would have to be addressed on an individual basis.

Diagnostic methods applicable to non-reacting flows are tabulated in Table IV. The methods listed here, while similar to those in Table III, are less problematic and more amenable to quantitative information due to the nature of the flow.

Table IV

Summary of Methods (Flow Field)
Non-reacting Flow Imaging

Method	Status	Merits	Obstacles
Tracers (PLIF, Mie, exciplex, Rayleigh, laser marking, etc...)	-done with particles (Al_2O_3, TiO_2, ketones, fuel)	-model validation -mixing, phase change -useful for screening -simple -semi-quantitative and quantitative	-safety -possible facility limitations
Focused Schlieren (density gradients)	-well developed -done to 10 atm	-mark heat release, phase change locations -simple and economical -qualitative movies, >8K frames/sec -potential 3-D	-non specific, qualitative information
PLIF, Mie, Rayleigh, Raman, CARS	-as per reacting flows but simpler, and more quantitative		

Non-reacting flows offer the best opportunity for acquisition of quantitative fundamental data useful in evaluation of code submodels. Compared with reacting flow studies, non-reacting flow experiments have the advantage of greater versatility and choice in selection of venue, but at the expense of simulating correct flow chemistry and heat release. The utilization of any of the above-listed diagnostic methods will facilitate the critical understanding of mixing processes expected to be exhibited in the ASCR.

Table V

Summary of Methods (Sprays)

Method	Status	Merits	Obstacles
Elastic Scattering	-mature method -qualitative	-simple -two dimensional data	-qualitative -nonspecific
PLIF (dopant or fuel)	-used at 30 atm	-simple -two dimensional data	-pressure effects -soot interference
Phase Doppler	-commercial instrument -point measurement	-gives droplet size -gives velocity -high accuracy -gives number density	-geometry limited -untested at high pressure -point measurement
Laser Diffraction (Malvern)	-commercial instrument -line-of-sight	-gives size	-droplet geometry limited (spherical) -index of refraction/ gradient concerns
Transit Time Laser Doppler Anemometry (TTLDA)	-PDA derivative	-gives simultaneous size and velocity -simple technique -not geometry limited	-droplet size limitation
Line-of-Sight Extinction	-mature method (line-of-sight)	-simple	-not spatially resolved

The techniques listed in Table V were determined by the working group to be those best suited for evaluation of sprays at AST conditions. There is presently not a large database

for sprays at high pressure. Most fuel injectors for combustors are examined for droplet size by at least one of the methods shown, but these tests are limited to ambient temperature and pressure, and generally to confined systems. Concerns that must be addressed include how best to correlate these experiments with actual in-situ performance. Moreover, since the AST combustor environment exceeds the critical conditions of the fuel, a question is: How is the fuel affected when it is injected in a supercritical environment? The answers to these concerns in addition to any related information gained in the area of sprays at AST conditions will greatly add to the store of knowledge presently available.

As combustor pressure increases, greater quantities of soot can be expected to be produced. Therefore, soot measurements can be considered critically important for two primary reasons. First, soot affects the amount of heat transfer to the materials in the combustor through radiation, and thus can play a role in reducing liner, or other subcomponent material integrity. Second, environmental factors may come into play because soot particles are potential nucleation sites for localized cloud formation. In addition, chemical kineticists in conjunction with modelers wish to decipher the mechanisms of soot formation, chain formation and agglomeration. Table VI examines these concerns and lists those diagnostic methods that the working group deemed best suited for characterization of soot, and soot formation in the ASCR environment.

Table VI

Summary of Methods (Soot)

Method	Status	Merits	Obstacles
Line-of-Sight Extinction	-done to 10 atm (soot vol. fraction)	- ~20% error -simple	-polycyclic aromatic hydrocarbon (PAH) fluorescence
2-Angle Scattering	-done to 10 atm	-spatially resolved	-limited optical access -particle size limitations
Laser-Induced Incandescence (non optically thick locations)	-done to 50 atm in diesel and rockets (soot vol. fraction)	-not influenced by fluorescence -two dimensional data -multi-laser line choices -determine soot formation location	-pressure effects -does not give particle size
Probe Sampling (DFWM, Photothermal, Photoacoustic. etc...)	-undeveloped	-rapid, real-time measurements -mostly simple -potential high accuracy	-sample line problems

Velocity measurements of droplets and particulates expected to be encountered at AST conditions were determined to be obtainable by the methods listed in Table VII.

Table VII

Summary of Methods (velocity)

Method	Status	Merits	Obstacles
Laser Doppler Velocimetry (LDV)	-mature -1, 2, and 3 components	-accurate u′ and u_{mean}	-requires seeding -point measurement
Particle Imaging Velocimetry (PIV)	-less mature	-two or three dimensional data	-requires seeding -high turbulence interference limitations
Phase Doppler Anemometry (PDA) and Transit Time LDV	-similar to LDV	-gives particle size	-optical access -beam steering -requires seeding
Tagging	-less developed -multiple variations	-may be useful at the exit plane	-only one component

Velocity measurements are especially relevant in the fuel-injection region, or any region where two or more fluid streams interact. The data obtained by the above techniques will provide critical input and feedback on jet penetration, turbulence and mixing quality.

RECOMMENDATIONS

To ensure that advanced diagnostics will play an important contributory role in the Advanced Subsonics Technology Program, validation and calibration experiments under controlled AST conditions in small-scale facilities will be required. These scaled facilities will provide the data base which is presently lacking for several critical parameters which include extinction coefficients, rotational-energy transfer rates, quench rates, spectral models, and polycyclic aromatic hydrocarbon (PAH) spectra.

Many of the diagnostic methods discussed and proposed for application in the AST program utilize common equipment, making it quite possible for individual laboratories to be capable of multiple-type experiments.

As previously stated, advanced optical diagnostics in high pressure regimes approaching that expected for the AST program have already been initiated in Japan and Germany. To properly study the combustion processes at AST conditions, facilities must be established in the United States that will provide the capability of creating environments similar to that in the ASCR but under tractable conditions. In addition, systematic studies under controlled conditions are critically needed to validate CFD submodels. These studies should be collaborative between CFD and diagnostic researchers.

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